Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
12 (2008) 1843–1863
RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS
www.elsevier.com/locate/rser

Assessment and statistics of Brazilian hydroelectric power plants: Dam areas versus installed and firm power

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Received 20 February 2007; accepted 11 April 2007

Abstract

The Brazilian relief, predominantly composed by small mountains and plateaus, contributed to formation of rivers with high amount of falls. With exception to North-eastern Brazil, the climate of this country are rainy, which contributes to maintain water flows high. These elements are essential to a high hydroelectric potential, contributing to the choice of hydroelectric power plants as the main technology of electricity generation in Brazil. Though this is a renewable source, whose utilized resource is free, dams must to be established which generates a high environmental and social impact. The objective of this study is to evaluate the impact caused by these dams through the use of environmental indexes. These indexes are ratio formed by installed power with dam area of a hydro power plant, and ratio formed by firm power with this dam area. In this study, the greatest media values were found in South, Southeast, and Northeast regions respectively, and the smallest media values were found in North and Mid-West regions, respectively. The greatest encountered media indexes were also found in dams established in the 1950s. In the last six decades, the smallest indexes were registered by dams established in the 1980s. These indexes could be utilized as important instruments for environmental impact assessments, and could enable a dam to be established that depletes an ecosystem as less as possible.

Keywords: Hydroelectric power plants; Dam area; Environmental index; Brazil

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.04.005

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1. Introduction

Various electricity generation technologies are available, and their priorities depend on potentialities of a determined region or country. In 2005, in Brazil, 83.4% of generated electricity, and 76.06% of installed power came from hydroelectric power plants, being that 68.76% of installed power was provided by hydropower plants, cited in this work (with an overall installed capacity of 64.05 GW [1]. The priority devoted to this technology is due to high flow of water in almost all Brazilian river basins. As much as 12% of all fresh surface water disposed all over the world is available in Brazil due to high rain level in its territory [2].

Brazilian plateaus, which are largely distributed in its territory, also contribute to an enormous hydroelectric potential due to presence of hills and mountains, which are responsible by altitudes variation of rivers and hence, formation of falls. Most of these plateaus are in altitudes that vary between 200 and 1000 m high, where most of Brazilian population and industries are encountered.

Even if Brazilian hydroelectric potential is relatively high, the medium rate of utilization is solely 27.24% (taking into account that hydroelectric potential accounted all over Brazil is 260.09 GW), varying dramatically depending on the state and river basin, while in countries such as USA, Japan, and EU countries where about 70% of its potential has been utilized [1].

Table 1 focuses all installed hydroelectric power and hydroelectric potential in Brazilian states and regions.

In Northern Brazil, due to the small population, low industrialization level, and the high installation expenditure of transmission and distribution systems due to large distances between hydropower plants and customers, the medium rate of utilization of its hydroelectric potential is small compared with other Brazilian regions. Due to these and other motives that, the electricity supply in this region is based mainly upon diesel-powered engines. With the ever-increasing environmental restrictions, the trend is to avoid the installation of hydropower plants in plain regions such as in the center of Amazonas River basin, where Balbina and Samuel hydropower plants were installed. The operation of these plants started in late 1980s, however assessments carried out before their installations did not take into account their high environment impacts (large forestry areas were

Table 1
Installed hydroelectric power, hydroelectric potential, and utilization rate of hydroelectric potential by Brazilian states and regions [3]

State	Installed power (MW)	Potential (MW)	Rate
North	8274	111,022	7.45
Rondônia	255	14,697	1.73
Acre	–	1058	–
Amazonas	282	20,469	1.38
Roraima	5	5262	0.10
Pará	6696	61,227	10.94
Amapá	68	1807	3.76
Tocantins	969	6502	14.90
Northeast	10,466	25,995	40.26
Maranhão	113	2574	4.38
Piauí	113	549	20.52
Ceará	4	25	16.00
Rio Grande do Norte	–	2	–
Paraíba	4	11	32.00
Pernambuco	755	1952	38.68
Alagoas	3712	4182	88.76
Sergipe	15	4165	36.02
Bahia	4266	12,535	34.03
Southeast	23,695	44,612	53.11
Minas Gerais	11,971	2471	48.45
Espírito Santo	355	1309	27.12
Rio de Janeiro	114	3367	33.86
São Paulo	10,229	15,226	67.18
South	19,307	4313	44.77
Paraná	1478	23,977	61.64
Santa Catarina	1672	7692	21.74
Rio Grande do Sul	2855	11,461	24.91
Mid-West	9114	35,334	25.79
Mato Grosso do Sul	2649	5961	44.43
Mato Grosso	1432	16,664	8.60
Goiás	5007	12,679	39.49
Distrito Federal	26	30	86.67
Brazil	70,858	260,093	27.24

inundated). Their projects were conceived in the 1970s and their operation started at following decade. The future projects of hydro power plants for this region concern with native population and high environment and social impacts that installation of transmission and distribution grids could to cause.

Contrary to Northern Brazil, the hydroelectric potential is mostly took advantage in Southeast, South, and Northeast regions, respectively. To supply electricity to the most populous and industrialized states (such as São Paulo state), hydropower plants have been installed in more distant regions such as some regions of state of Minas Gerais, Southern and Mid-Western Brazil. This fact has also been stimulated due to the introduction of transmission lines with fewer losses (such as direct current and higher tension technologies).

As previously explained, one of the main environmental problems caused by hydropower plants is formation of dams, which substitute the previously existent landscape which could be native vegetation, urban zones, farms, etc. Not solely environmental problems generally appear but some economic activities could be also affected. Due to environmental problems caused by these plants, older projects have been modified to mitigate environment, economic and social problems becoming possible, inclusively, to decrease the overall expenditure of this installation. One example that could be cited is Belo Monte hydropower plant, whose project has been modified with objective to diminish the dam area (the previous dam area was three times as much as the area determined by current project).

Various works and technical reports have been published to focus on impacts caused due to installation and operation of hydropower plants, especially about the formed dams [4–14], and some actions that could be performed to mitigate them [15–18]. Other impacts must be also considered, such as greenhouse gases production and pollution of water due to decomposition of organic matter [19].

About 2000 dams were established in Brazil, being that more than 1500 are out of use, inclusively at conditions that are not been known. Optimization of the use of water in a river basin could help to a major electricity generation [20–22].

Despite the problems caused by hydropower plants during their installation, this technology is largely suggested whether cautions are taken into account [24].

2. Large hydroelectric power plants in Brazil

Most of the electricity produced in Brazil is provided by large power plants. The installed capacity by this power source is as high as 71 GW [23]; and considering all power plants cited in this work about 64 GW[1] was amounted. Some of the cited plants have been run since 1950s due to development of newer technologies of generation, transmission and distribution. At last decades, some of older small hydropower plants (SHPs) have been phased out due to high depreciation and hence, due to higher expenditures of operation and maintenance, facing the lower expenditures obtained by newer and larger plants.

However, opposite opinions to the installation of these plants have increased due to failures occurred in the past such as occurred with Tucuruí and Balbina hydropower plants, which have contributed to enormous environmental and social impacts.

Various hydropower plant projects are in study, and some of them are large plants such as Belo Monte (Xingu River), Santo Antonio and Jirau power plants, both in Madeira River. Despite these projects have been optimized (the current projects are more environmentally friendly than the older ones), various organizations are contrary to the construction of these plants.

Some hydropower plants were solely suggested, such as Óbidos hydropower plant, which would be installed in Amazonas River. This project which was conceptualised in the 1960s would have a maximum installed power as much as 70 GW, and its formed dam area would be as much as 180,000 km^2 [24].

In Brazil, as occurred all over the world, various hydropower plants were installed mainly between 1970 and 1975 due to high economic growth [4].

[1]Considering all hydropower plants cited in this work (whose power is higher than 30 MW and/or whose area dam is higher than 3 km^2).

3. Assessment of large hydroelectric power plants

3.1. Analysis of findings of cited plants

The relief, and water flows of rivers and their variation during a determined period has rough differences depending upon studied region.

Table 2 focuses on the largest hydropower plants, the installed power, the formed dam areas, and its environmental indexes. These indexes are ratios of installed power or firm power of a hydropower plant with the lake area formed by it. It could be used as a decision-making tool to evaluate the possibility to install a hydropower plant with low environment, economic, and social impact. These indexes have already been utilized in previous studies such as performed by Mariotoni and Badanhan [25].

In this table, SHPs were not cited. As cited by ANEEL, this type of plant has a maximum installed power of 30 MW and a maximum formed lake area of 3 km^2 [26]. The SHPs have been investigated and utilized as seen on various works [5,27–31].

South-eastern Brazil region contains a major amount of hydropower plants (72 plants were cited), followed by Southern (27 plants), Mid-Western (18 plants), North-eastern (11 plants), and Northern (7 plants).

The differences among environment indexes do not depend on the installed power and formed lake area. This difference is enormous as might be seen in power plants such as Foz do Areia (whose indexes are 838 and 288), Sobragi (whose indexes are 600 and 380) and, on the other hand, Balbina (whose indexes are 0.11 and 0.03) [26].

Significant differences were also observed among the calculated ratios firm power/installed power of studied hydropower plants. These values are in a range between 0.12 (in the case of Henry Borden) and 0.93 (in the case of Guaporé). The small values were generally found in power plants whose rivers have a significant variation of water flow during a year and (or) whose dams have small storage capacity or, in the case of Henry Borden, problems with water supply. In some power plants turbines and generators at a quantity more than necessary were installed, and in the other hand, in some plants an additional power could be installed taking advantage the possibility originally predicted in those projects.

Among the cited hydroelectric power plants in this work, the first established one was Fontes in 1908, with high environmental indexes and high ratio firm power/installed power. The world's largest hydropower plant is Itaipu, whose installed power is 12,600 MW. Some hydropower plants cited in this work have installed power less than 30 MW; however, they can not be considered as SHPs since their dam areas are larger than 3 km^2, such as Araras, Curua-Una, Pedra, and others. These plants have small environmental indexes.

The world's largest dam area to energy generation purpose is comprised by Sobradinho, whose area is 4214 km^2. Small dam areas are seen in power plants such as Guaricana and Sobragi, with 0.1 km^2 each. The items that must take into account in these plants are high environmental indexes.

More-stringent laws and presence of areas protected by law became the installation of hydropower plants more difficult, especially for those that have small environment indexes. Nowadays it is more difficult to find a suitable place to install a hydropower plant with high environmental index, as it is difficult to think about the possibility to project a plant with smaller environmental index, solely whether the formed lake will be also utilized for other purposes such as irrigation, flow control of the river, or water supply to a city, etc. [4].

Table 2
Some findings about the cited hydroelectric power plants [32–58]

Region	Name	River	Year of operation start	Installed power (MW)	Firm power (MW)	Ratio firm power/installed power	Dam area (km^2)	Ratio installed power/dam area	Ratio firm power/dam area
North	Coaracy Nunes	Araguari	1975	40	–	–	23	1.74	–
	Curuá-Una	Curuá-Una	1977	30	24	0.8	78	0.38	0.31
	Samuel	Jamari	1989	216	70	0.32	559	0.39	0.13
	Lajeado	Tocantins	2001	903	527	0.58	630	1.43	0.84
	Peixe Angical	Tocantins	2006	483	271	0.56	194	2.49	1.4
	Tucuruí	Tocantins	1985	8370	4140	0.49	2430	3.44	1.7
	Balbina	Uatumã	1989	250	64	0.26	2360	0.11	0.03
Northeast	Araras	Acarau	1958	4	–	–	97	0.04	–
	Funil	Das Contas	1962	30	16	0.53	4	7.5	4
	Pedra	Das Contas	1978	20	*	–	101	0.2	–
	Pedra do Cavalo	Paranaguassu	1994	160	56	0.35	186	0.86	0.3
	Boa Esperança	Parnaíba	1970	237	143	0.6	350	0.68	0.41
	Itaparica	São Francisco	1990	1480	959	0.65	835	1.77	1.15
	Moxotó	São Francisco	1977	400	225	0.56	93	4.3	2.42
	Paulo Afonso	São Francisco	1955	4113	3606	0.88	35	117.51	103.03
	Sobradinho	São Francisco	1979	1050	531	0.51	4214	0.25	0.13
	Xingó	São Francisco	1994	3162	2139	0.68	60	52.7	35.65
	Itapebi	Jequitinhonha	2002	225	99	0.44	31	7.26	3.19
Mid-West	Ponte de Pedra	Correntes	2004	176	132	0.75	16	11	8.25
	Corumbá I	Corumbá	1988	375	209	0.56	65	5.77	3.22
	Corumbá IV	Corumbá	2005	127	76	0.6	173	0.73	0.44
	Guaporé	Guaporé	2003	120	112	0.93	4	28.57	26.67
	Itiquira	Itiquira	2002	156	107	0.69	3	52	35.67
	Jauru	Jauru	2002	122	80	0.66	4	30.5	20
	Manso	Manso	2000	210	92	0.44	427	0.49	0.22
	Itumbiara	Paranaíba	1974	1140	508	0.45	399	2.86	1.27
	Cachoeira Dourada	Paranaíba	1966	329	208	0.63	37	8.89	5.62
Mid-West	Emborcação	Paranaíba	1976	596	249	0.42	228	2.61	1.09
	São Simão	Paranaíba	1978	855	641	0.75	386	2.22	1.66

	Paranoá	Paranoá	1960	30	13	0.43	40	0.75	0.33
	Queimado	Preto	2003	52	29	0.56	20	2.6	1.45
	Cana Brava	Tocantins	2002	450	274	0.61	139	3.24	1.97
	Serra da Mesa	Tocantins	1996	1275	671	0.53	1784	0.71	0.38
	Ilha Solteira	Paraná	1971	1722	975	0.57	539	3.19	1.81
	Jupiá	Paraná	1974	776	443	0.57	164	4.73	2.7
	Porto Primavera	Paraná	1998	770	509	0.66	1125	0.68	0.45
South	Monte Claro	Antas	2004	130	59	0.45	1	130	59
	Guaricana	Arraial	1957	36	14	0.39	0.1	360	140
	Campos Novos	Canoas	2006	880	378	0.43	35	25.14	10.8
	Capivari-Cachoeira	Capivari	1970	260	109	0.42	14	18.57	7.79
	Quebra Queixo	Chapecó	2003	120	60	0.5	6	20	10
	Foz do Areia	Iguaçu	1977	1676	576	0.34	2	838	288
	Salto Caxias	Iguaçu	2000	1240	605	0.49	144	8.61	4.2
	Salto Osório	Iguaçu	1975	1078	522	0.48	41	26.29	12.73
	Salto Santiago	Iguaçu	1980	1420	723	0.51	208	6.83	3.48
	Segredo	Iguaçu	1992	1260	603	0.48	82	15.37	7.35
	Dona Francisca	Jacuí	2001	125	78	0.62	19	6.58	4.11
	Itauba	Jacuí	1978	512	190	0.37	17	30.12	11.18
	Jacuí	Jacuí	1963	180	123	0.68	5	36	24.6
	Passo Real	Jacuí	1973	158	68	0.43	221	0.71	0.31
	Campo Mourão	Mourão	1969	8	–	–	11	0.73	–
	Itaipu (Brazilian side)	Paraná	1982	6300	4306	0.68	675	9.33	6.38
	Passo Fundo	Passo Fundo	1973	220	119	0.54	149	1.48	0.8
	Barra Grande	Pelotas	2005	690	381	0.55	92	7.5	4.14
South	Machadinho	Pelotas	2003	1140	529	0.46	79	14.43	6.7
	Canastra	Santa Maria	1956	43	24	0.56	0.5	86	48
	Canoas I	Paranapanema	1998	42	29	0.69	16	2.63	1.81
	Canoas II	Paranapanema	1998	36	24	0.67	12	3	2
	Capivara	Paranapanema	1978	310	165	0.53	288	1.08	0.57
	Chavantes	Paranapanema	1970	207	86	0.42	299	0.69	0.29
	Rosana	Paranapanema	1987	186	89	0.48	109	1.71	0.82
	Taquaruçú	Paranapanema	1990	277	101	0.36	53	5.23	1.91
	Ourinhos	Paranapanema	2004	22	12	0.55	2	11	6
Southeast	Capim Branco I	Araguari	2006	240	155	0.65	19	12.63	8.16
	Capim Branco II	Araguari	2006	210	131	0.62	44	4.77	2.98

Table 2 (*continued*)

Region	Name	River	Year of operation start	Installed power (MW)	Firm power (MW)	Ratio firm power/installed power	Dam area (km^2)	Ratio installed power/dam area	Ratio firm power/dam area
	Miranda	Araguari	1997	408	202	0.5	51	8	3.96
	Nova Ponte	Araguari	1994	510	276	0.54	447	1.14	0.62
	Salto do Iporanga	Assungui	1989	37	–	–	3	12.33	–
	Americana	Atibaia	1949	30	9	0.3	11	2.73	0.82
	Aimorés	Doce	2005	330	172	0.52	31	10.65	5.55
	Candonga	Doce	2003	140	65	0.46	3	46.67	21.67
	Mascarenhas	Doce	1972	181	127	0.7	4	45.25	31.75
	Água Vermelha	Grande	1978	1396	746	0.53	643	2.17	1.16
	Camargos	Grande	1958	46	21	0.46	76	0.61	0.28
	Estreito	Grande	1963	1050	495	0.47	590	1.78	0.84
	Furnas	Grande	1964	1216	598	0.49	1443	0.84	0.41
	Igarapava	Grande	1998	210	136	0.65	37	5.68	3.68
	Itutinga	Grande	1955	52	–	–	2	26	–
	Jaguara	Grande	1970	424	336	0.79	33	12.85	10.18
	Marimbondo	Grande	1971	1440	726	0.5	426	3.38	1.7
	Peixoto	Grande	1950	478	295	0.62	250	1.91	1.18
	Porto Colômbia	Grande	1970	328	185	0.56	144	2.28	1.28
Southeast	Volta Grande	Grande	1968	380	229	0.6	222	1.71	1.03
	Rosal	Itabapoana	1999	55	30	0.55	1	55	30
	Jaguari	Jaguari	1971	28	14	0.5	70	0.4	0.2
	Irapé	Jequitinhonha	2006	360	206	0.57	138	2.61	1.49
	Itapebi	Jequitinhonha	2002	225	99	0.44	31	7.26	3.19
	Alecrim	Juquiá-Guaçú	1974	72	–	–	2	36	–
	Barra	Juquiá-Guaçú	1996	40	22	0.55	2	20	11
	Fumaça	Juquiá-Guaçú	1964	37	–	–	7	5.29	–
	Fontes	Lages	1908	130	104	0.8	4	32.5	26
	Pereira Passos	Lages	1961	99	51	0.52	1	99	51
	Santa Clara	Mucuri	2003	60	28	0.47	8	7.5	3.5
	Funil	Paraíba do Sul	1961	216	121	0.56	40	5.4	3.03
	Ilha dos Pombos	Paraíba do Sul	1924	187	115	0.61	4	46.75	28.75
	Nilo Peçanha	Paraíba do Sul	1953	378	335	0.89	4	94.5	83.75
	Santa Branca	Paraíba do Sul	1960	56	32	0.57	28	2	1.14

	Paraibuna	Paraibuna	1978	85	50	0.59	177	0.48	0.28
	Sobragi	Paraibuna	1998	60	38	0.63	0.1	600	380
	Ilha Solteira	Paraná	1971	1722	975	0.57	539	3.19	1.81
	Jupiá	Paraná	1974	776	443	0.57	164	4.73	2.7
	Porto Primavera	Paraná	1998	770	509	0.66	1125	0.68	0.45
	Canoas I	Paranapanema	1998	42	29	0.69	16	2.63	1.81
	Canoas II	Paranapanema	1998	36	24	0.67	12	3	2
	Capivara	Paranapanema	1978	310	165	0.53	288	1.08	0.57
	Chavantes	Paranapanema	1970	207	86	0.42	299	0.69	0.29
	Jurumirim	Paranapanema	1962	98	47	0.48	213	0.46	0.22
	Piraju	Paranapanema	2002	81	47	0.58	9	9	5.22
	Rosana	Paranapanema	1987	186	89	0.48	109	1.71	0.82
	Salto Grande	Paranapanema	1958	74	55	0.74	8	9.25	6.88
	Taquaruçú	Paranapanema	1990	277	101	0.36	53	5.23	1.91
	Ourinhos	Paranapanema	2004	22	12	0.55	2	11	6
	Caconde	Pardo	1965	80	33	0.41	31	2.58	1.06
	Euclides da Cunha	Pardo	1960	109	49	0.45	1	109	49
	Limoeiro	Pardo	1958	32	15	0.47	3	9.7	4.55
	Henry Borden	Pedras	1926	889	108	0.12	139	6.4	0.78
	Picada	Peixe	2005	50	27	0.54	1	50	27
Southeast	Guilman-Amorim	Piracicaba	1997	140	66	0.47	1	140	66
	Sá Carvalho	Piracicaba	1994	78	58	0.74	2	39	29
	Bariri	Tietê	1966	143	66	0.46	63	2.27	1.05
	Barra Bonita	Tietê	1963	141	45	0.32	312	0.45	0.14
	Ibitinga	Tietê	1969	132	74	0.56	114	1.16	0.65
	Nova Avanhandava	Tietê	1982	347	139	0.4	210	1.65	0.66
	Promissão	Tietê	1975	264	104	0.39	530	0.5	0.2
	Três Irmãos	Tietê	1990	1292	648	0.5	951	1.36	0.68
	Porto Estrela	Santo Antonio	2002	112	56	0.5	4	28	14
	Salto Grande	Santo Antonio	1963	102	–	–	6	17	–
	Suíça	Santa Maria	1965	30	15	0.5	0.6	50	25
	Três Marias	São Francisco	1962	396	239	0.6	1059	0.37	0.23
	Itupararanga	Sorocaba	1912	56	–	–	30	1.87	–
	Itumbiara	Paranaíba	1974	1140	508	0.45	399	2.86	1.27
	Cachoeira Dourada	Paranaíba	1966	329	208	0.63	37	8.89	5.62
	Emborcação	Paranaíba	1976	596	249	0.42	228	2.61	1.09
	São Simão	Paranaíba	1978	855	641	0.75	386	2.22	1.66
	Queimado	Preto	2003	52	29	0.56	20	2.6	1.45

Fig. 1 focuses on relationship between formed dam areas and installed power of cited plants, and Fig. 2 shows relationship between formed dam area and firm power of same plants.

3.2. Comparisons among regions

Table 3 focuses on overall installed powers, overall firm powers, and sum of dam areas of each Brazilian region. Table 4 focuses on media years of installed hydropower plant,

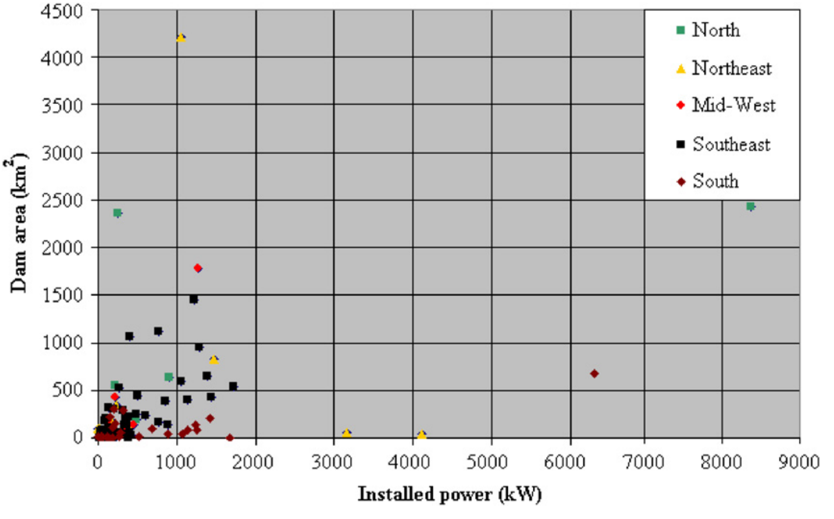

Fig. 1. Installed power and formed dam area of cited plants.

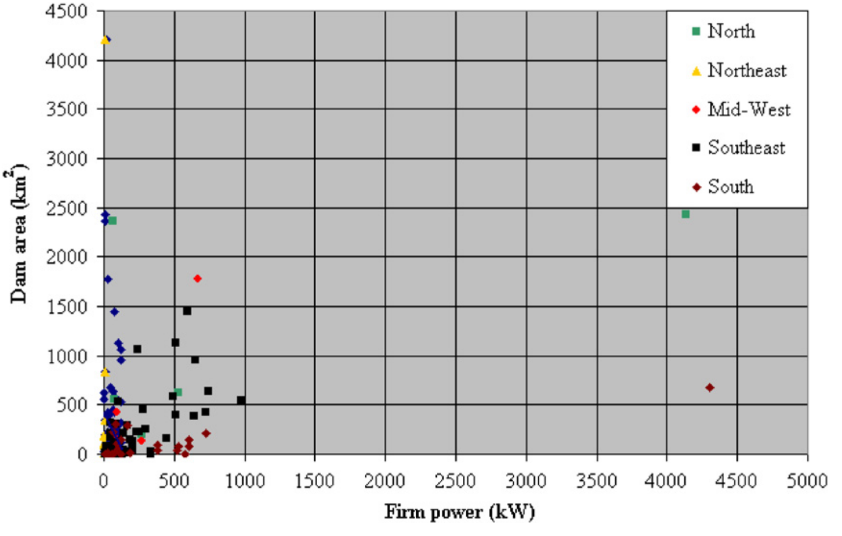

Fig. 2. Firm power and formed dam area of cited plants.

Table 3
Findings of each region

	Overall installed power (MW)	Overall installed power percentage	Overall firm power (MW)	Overall firm power percentage	Dam area (km^2)	Overall dam area percentage
North	10,292	14	5096	13	6274.1	19
Northeast	10,656	15	7675	19	5975	18
Mid-West	9281	13	5328	13	5553.2	17
Southeast	18,556	26	9973	25	2580.6	8
South	23,160	32	12,108	30	12,361	38
Brazil	71,945	100	40,180	100	32,744	100

Table 4
Media of each region

	Medium year of operation start	Medium power (MW)	Medium firm power (MW)	Medium dam area (km^2)	Medium ratio installed power/dam area	Medium ratio firm power/dam area	Medium ratio installed power/firm power
North	1989	1470	849	896	1.64	0.95	0.50
Northeast	1978	989	864	546	1.81	1.58	0.58
Mid-West	1989	516	296	308	1.67	0.96	0.60
South	1984	714	396	94	7.64	4.23	0.49
Southeast	1976	349	204	159	2.20	1.28	0.50

media installed powers, media firm powers, media dam areas, media ratios installed power/dam area, media ratios firm power/dam area, and media ratios firm power/installed power. The data of the findings in both the tables are according to each region.

The results in the Table 4 show that the oldest plants are localized in the Southeast, Northeast and South regions, where, in this order, the greatest populations were found. The plants of North and Mid-West are newer face the development that these regions have been nowadays witnessing.

The greatest media powers were found in North and Northeast regions and the smaller media power was found in the Southwest region. The smaller media found in this region is compensated by major amount of power plants. However, the dam areas of some power plants found in the North and Northeast regions such as Balbina, Sobradinho, and Tucuruí are the greatest installed in Brazil and would be virtually impossible to install them in regions such as Southeast and South due to higher population density found in these regions, to higher amount of cities, villages and communities and, hence, to the higher economic and social impact that a power plant could form.

The greatest environmental indexes were found in the South region, and the smallest media indexes were found in North and Mid-West regions with large areas containing small demographic densities.

The differences among media ratios firm power/installed power of different regions are small. The smaller medium ratio was found in the South region, and the greatest medium ratio was found in the mid-West region.

The calculation of means hide the differences among hydropower plants' findings such as the case of Itaipu, whose power is much larger than the second largest power plant (Tucuruí hydropower plant, in the North region, whose power is much larger than provided by other plants in the North region such as Lajeado). The difference between dam areas is also large such as found in Northeast region where Sobradinho is installed.

3.3. Comparisons among cited rivers

Tables 5 and 6 focus findings extracted from rivers that contain more hydropower plants. The cited ones contain at least two operational hydropower plants, not considering the SHPs. Grande River contains 11 hydropower plants, the highest amount of operational plants among the studied rivers. This river is localized in the states of São Paulo and Minas Gerais, in the Southeast region.

Table 5 focuses on the number of hydroelectric power plants, overall installed powers, overall firm powers, and sum of dam areas. Table 6 focuses on media years of installed hydropower plant, media installed powers, media firm powers, media dam areas, media ratios installed power/dam area, media ratios firm power/dam area, and media ratios firm power/installed power.

The media year of operation start of installed hydroelectric power plants in Paraíba do Sul river (1950) focus that some of oldest hydropower plants were established there. Other rivers such as Pardo (1961), Grande (1968), and others, also focus that operation start of these power plants was not recent. Afterwards, most of power plants in rivers such as Tocantins and Jequitinhonha were established.

The greatest media installed and firm power were found in rivers such as Paraná, São Francisco and Tocantins due to the installation of some of the greatest Brazilian power plants. The greatest values were found in the Paraná River due to the presence of Itaipu, the greatest Brazilian hydropower plant.

Table 5
Findings of each river

	Number of plants	Overall installed power (MW)	Overall firm power (MW)	Dam area (km^2)
Araguari	4	1368	764	561
Doce	3	651	364	38
Grande	11	7020	3767	3866
Iguaçu	5	6674	3029	477
Jacuí	4	975	459	262
Jequitinhonha	2	810	404	200
Juquiá-Guaçú	3	149	22	11
Paraíba do Sul	4	837	603	76
Paraná	4	12,836	8160	4331
Paranaíba	4	5840	3212	2100
Paranapanema	10	2413	1161	1788
Pardo	3	221	97	35.3
São Francisco	6	10,601	7699	6296
Tietê	5	2319	1076	2180
Tocantins	5	11,481	5883	5177.1

Table 6
Media of each river

	Medium year of operation start	Medium installed power (MW)	Medium firm power (MW)	Medium ratio firm power/ installed power	Medium dam area (km^2)	Medium ratio installed power/dam area	Medium ratio firm power/dam area
Araguari	2001	342	191	0.58	140	6.64	3.93
Doce	1993	217	121	0.56	13	34.19	19.66
Grande	1968	638	377	0.57	351	5.38	1.98
Iguaçu	1985	1335	606	0.46	95	179.02	63.15
Jacuí	1979	244	115	0.53	66	18.35	10.05
Jequitinhonha	2003	270	135	0.48	67	5.71	2.34
Juquiá-Guaçú	1978	50	22	0.55	4	20.43	3.67
Paraíba do Sul	1950	209	151	0.66	19	4.66	2.25
Paraná	1981	1834	1166	0.61	619	3.79	2.64
Paranaíba	1974	730	402	0.56	263	4.14	2.57
Paranapanema	1987	142	68	0.54	105	4.08	2.07
Pardo	1961	74	32	0.44	12	40.43	18.20
São Francisco	1976	1767	1283	0.65	1049	29.49	23.77
Tietê	1974	387	179	0.44	363	1.23	0.54
Tocantins	1998	2296	1177	0.55	1035	3.60	2.41

The greatest media dam area was seen in São Francisco and Tocantins rivers mainly due to the presence of hydropower plants such as Sobradinho and Tucuruí, respectively. The lowest values were seen in Juquiá-Guaçú and Pardo rivers.

About the media environmental indexes, the greatest values were found in Iguaçu river, and the lower values were found in Tietê river.

3.4. Comparisons among decades of operation start of cited plants

Table 7 focuses on the number of hydroelectric power plants, overall installed powers, overall firm powers, and sum of dam areas, depending upon each decade of operation start. Table 8 focuses on the media values depending on the decade when the hydropower plants started their operation. With regard to the media installed or media firm power, the highest values were seen in the period 1971–1990, and the lowest values were seen in the period 1900–1920. However, this type of finding is limited due to the presence of solely two hydropower plants in the period 1900–1920. After 1941, the variation of studied values is extremely high, becoming unavailable a more accurate analysis.

In the period 2001–2006, more plants were cited, however, the media installed and firm powers were low if compared with other periods. Probably more plants will be established afterwards in this decade.

Figs. 3 and 4 focus on evolution of environmental indexes of power plants during the years when cited hydropower plants were established.

3.5. Analyses of standard deviations

In Tables 9–11, standard deviations were calculated with objective to measure the spread of values of findings evaluated in this work. In Table 6, it was observed that the greatest

Table 7
Findings of each decade of operation start of hydroelectric power plants

	Number of plants	Overall installed power (MW)	Overall firm power (MW)	Dam area (km^2)
1900–1910	1	130	104	4
1911–1920	1	56	0	30
1921–1930	2	1076	223	143
1931–1940	–	–	–	–
1941–1950	2	508	304	261
1951–1960	12	4973	4164	294.9
1961–1970	23	6123	3219	4998.6
1971–1980	24	15,469	7726	9003
1981–1990	11	19,130	10,725	8250
1991–2000	17	9656	5556	4377.1
2001–2006	25	7384	4031	1699.3

Table 8
Media of each decade of operation start

	Medium installed power (MW)	Medium firm power (MW)	Medium ratio firm power/ installed power	Medium dam area (km^2)	Medium ratio installed power/ dam area	Medium ratio firm power/ dam area
1900–1910	130.00	104.00	0.800	4.00	32.50	26.00
1911–1920	56.00	–	–	30.00	1.87	–
1921–1930	538.00	111.50	0.207	71.50	26.57	14.76
1931–1940	–	–	–	–	–	–
1941–1950	254.00	152.00	0.598	130.50	2.32	1.00
1951–1960	414.42	416.40	0.847	24.58	67.95	43.69
1961–1970	266.22	160.95	0.539	217.33	12.02	6.94
1971–1980	644.54	367.90	0.504	375.13	42.30	17.32
1981–1990	1739.09	1072.50	0.562	750.00	3.92	1.67
1991–2000	568.00	326.82	0.575	257.48	56.11	33.92
2001–2006	295.36	161.24	0.546	67.97	20.25	11.21

differences among years of operation start were seen in the Southwest region, where the first plants were installed and more plants were being installed nowadays. The lowest differences are seen in the North region because the development of this region has occurred more recently and the construction of first power plants began more recently. The standard deviations for the Northeast, Mid-West and South regions are almost the same.

A higher variability of installed and firm powers was seen in the North, Northeast and South region. There, many small and some great plants were installed.

The greatest variations among ratios firm power/installed power are seen in the North and Southeast regions, respectively. Balbina (in the North region) and Henry Borden (in the Southeast region), which contains the lowest ratios, contributed to the high standard deviations.

The presence of high dam areas in the Northeast (where Sobradinho hydropower plant is installed) and North (where Tucuruí and Balbina hydropower plants are installed) contributed to the high standard deviations of dam areas in these regions.

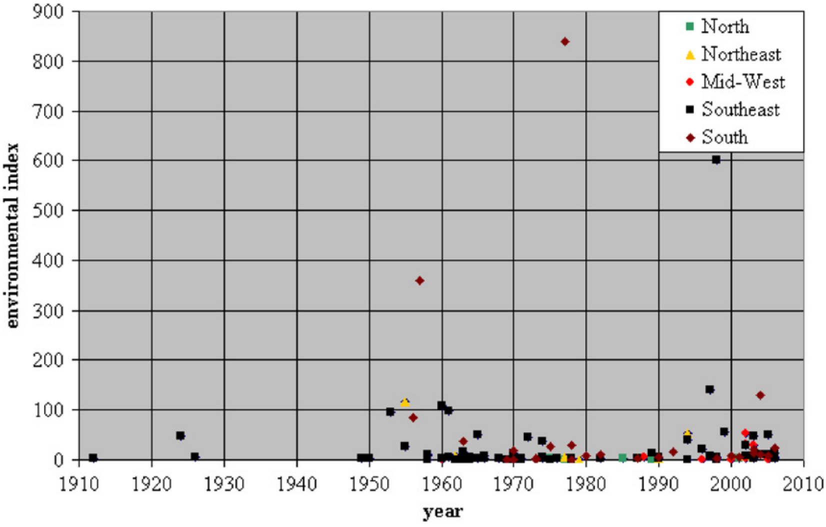

Fig. 3. Ratio of installed power/dam area of established hydropower plants during the years 1910–2010.

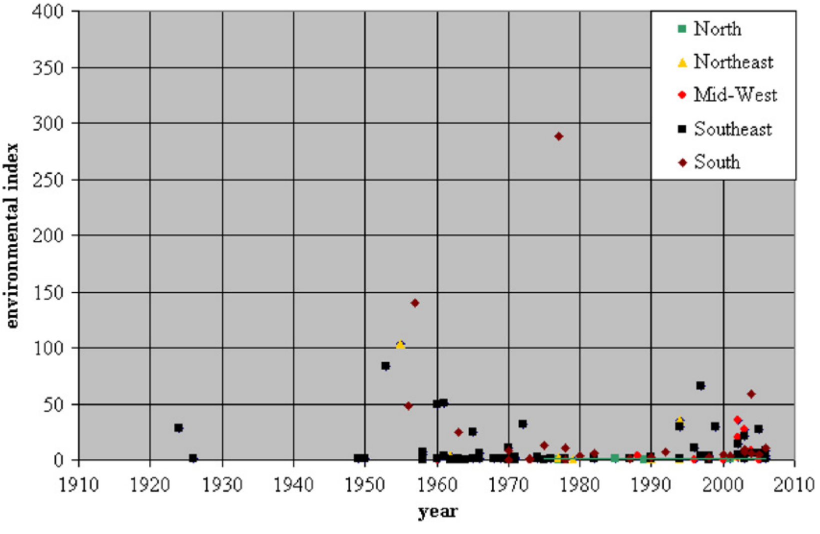

Fig. 4. Ratio of firm power/dam area of established hydropower plants during the years 1910–2010.

The greatest variations among environmental indexes were seen in the South region, and the lowest variations were seen in the North region because there generally the hydropower plants have low ratios such as Balbina hydropower plant.

The lowest standard deviations of installed or firm powers were seen in Juquiá-Guaçú and Pardo rivers due to the presence of solely small plants. The greatest standard deviation of dam areas was seen in São Francisco River, where plants such as Sobradinho (where a large dam area was found) and Paulo Afonso (where a small dam area was found) are

Table 9
Standard deviations of findings obtained to each region

	Year of operation start	Installed power (MW)	Firm power (MW)	Ratio firm power/ installed power	Dam area (km^2)	Ratio installed power/dam area	Ratio firm power/dam area
North	11.47	3057.37	1623.09	0.196	1049.18	1.24	0.70
Northeast	15.76	1404.93	1232.35	0.151	1239.63	36.51	34.30
Mid-West	15.47	484.24	269.55	0.131	463.50	13.95	10.30
South	15.82	1230.06	831.65	0.139	146.34	170.79	60.94
Southeast	22.26	391.58	214.14	0.193	290.04	74.08	48.52

Table 10
Standard deviations of findings obtained to each region

	Year of operation start	Installed power (MW)	Firm power (MW)	Ratio firm power/ installed power	Dam area (km^2)	Ratio installed power/dam area	Ratio firm power/dam area
Araguari	6.18	141.90	63.88	0.071	204.96	4.88	3.15
Doce	18.50	99.98	53.72	0.124	15.89	20.40	13.22
Grande	12.85	532.23	252.26	0.102	425.12	7.66	2.89
Iguaçu	10.76	225.95	73.58	0.066	82.01	368.46	125.75
Jacuí	16.09	180.26	55.58	0.150	103.85	17.32	10.70
Jequitinhonha	2.31	77.94	61.78	0.076	61.78	2.68	1.20
Juquiá-Guaçú	16.37	19.40	–	–	2.89	15.36	6.35
Paraíba do Sul	17.37	132.29	129.37	0.154	18.00	4.65	2.59
Paraná	12.09	2019.62	1404.83	0.054	396.24	2.96	2.01
Paranaíba	4.87	321.82	192.28	0.146	156.68	2.94	2.09
Paranapanema	14.81	108.04	47.93	0.118	120.50	3.72	2.17
Pardo	3.61	38.89	17.01	0.029	16.70	59.49	26.73
São Francisco	15.28	1535.87	1342.30	0.129	1611.42	47.73	41.24
Tietê	10.30	451.85	231.92	0.086	332.16	0.70	0.38
Tocantins	8.09	3412.15	1665.39	0.045	1022.37	3.01	2.15

localized. The greatest standard deviations of ratio installed or firm power/dam area, were found in Iguaçu River due to the presence of Foz do Areia hydropower plant.

In Table 11, standard deviations depending on each decade were calculated. High differences among installed power and firm power in the period 1921–1930 was cited due to the presence of Henry Borden power plant whose ratio firm power/installed power is low.

3.6. Future trends

As cited previously, the trend is, in the near future, to install solely hydropower plants with high environmental indexes; however, it will be difficult to install plants with extremely high ratios such as seen in Paulo Afonso hydropower plant. Considering both findings, the standard deviation of these information will probably be lower.

Table 11
Standard deviations of findings obtained for each decade of operation start of hydroelectric power plants

	Installed power (MW)	Firm power (MW)	Ratio firm power/ installed power	Dam area (km^2)	Ratio installed power/dam area	Ratio firm power/dam area
1900–1910	–	–	–	–	–	–
1911–1920	–	–	–	–	–	–
1921–1930	496.39	4.95	0.349	95.46	28.53	19.78
1931–1940	–	–	–	–	–	–
1941–1950	316.78	202.23	0.224	169.00	0.58	0.26
1951–1960	1168.88	1124.95	0.186	32.53	103.17	50.46
1961–1970	300.82	157.65	0.107	363.85	22.66	12.76
1971–1980	582.55	290.76	0.116	839.12	169.96	62.44
1981–1990	2842.90	1686.82	0.137	878.62	3.92	1.91
1991–2000	807.57	521.86	0.107	485.63	144.53	90.98
2001–2006	302.24	150.33	0.110	130.50	27.58	13.82

Some hydropower plants established in Brazil have an additional capacity that could be taken advantage in the near future. Instead of installing more hydropower plants, this additional power could be installed avoiding more environmental impact. Xingó power plant contains 3162 MW of installed capacity. However, the designed power is 5000 MW which will be attained when more turbines and generators will be installed.

The re-powering of older plants also contributes to increase their environment indexes due to the increase of installed power with low or without any environment impact. Nowadays, an electricity generation system is designed to be utilized for about 50 years having the possibility to install newer equipments. For systems established in the last 30 years, it is possible to attain an increase of installed power up to 50% [31].

Some large hydropower plants such as Belo Monte, Santo Antonio and Jirau are in project status. Based on a technical report performed by Tolmasquim [59], it was predicted that environmental indexes (solely considering the installed power) of these hydropower plants will be 25, 12.5, and 11.1, respectively. The medium environmental index of hydropower plants cited in this work was 2.20 (considering the installed power) and 1.23 (considering the firm power).

Other findings that might be considered are the electricity production in association with formed lake area by hydropower plant. This value depends enormously on the river flow variation during a period of time that a plant is operational, and electricity demand. This is also an efficient method to evaluate the environment impact caused by hydropower plants. However, the annual production of each power plant is more difficult to be obtained. Solely some power plants and companies dispose these data.

Another type of analysis of environmental impact caused by hydropower plants could be performed by calculated volume of reservoirs. This finding is currently utilized to calculate royalties and other financial expenditures as could be seen in homologate resolutions performed by ANEEL [60].

4. Conclusions

Findings such as environment indexes are important decision-making tools to evaluate the possibility to install a hydropower plant. Of course, the determination of its construction depends largely on other items such as economic, social, financial, and politic factors.

By a study of tables and figures focused on this study, it was possible to obtain some conclusions about the type of power plant and its environmental impact.

Firstly, it was observed that most of the hydroelectric power plants are installed in the Southeast region, the most industrialized and populous Brazilian region. However, various plants have been recently established in more distant regions due to their recent economic development and due to the lack of feasible places to install them in regions where the rate of utilized hydroelectric potential is already high, such as Southeast region.

Older hydropower plants are found in rivers localized in regions such as Southeast. There, a higher amount of plants are also found, such as Grande and Paranapanema rivers.

In periods between 2001–2006 and 1971–1980, more hydropower plants started their operations; however, in the period 1981–1990, more power was available mainly due to projects initialized in the previous decade.

The standard deviations showed an enormous spread of studied values, especially after 1951, when most of the large hydropower plants were installed. After this period, higher medium firm power and medium dam areas were detected as verified in the graphs in Figs. 3 and 4. High standard deviations were also found in regions such as North and Northeast due to high variation among installed and firm power and dam areas of hydropower plants. However, in the North and Mid-West regions, lower environmental indexes were found, and one of reasons is the high quantity of large dam areas.

High standard deviations were found in rivers such as Tocantins, Paraná and São Francisco due to the high variation of powers and dam areas among their power plants. In the Iguaçu river, the highest standard deviations of environmental indexes were encountered.

The values of installed and firm power and dam areas cited in this work do not consider SHPs. Of course, if their values were cited these values would be profoundly changed specially in the Southeast region where a higher amount of SHPs, the smallest media installed and firm power and lower media dam areas were found.

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